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FOR: MAGNETIC ENERGY STORAGE

REQUEST FOR PRIORITY UNDER 35 U.S.C. 119
AND THE INTERNATIONAL CONVENTION

Assistant Commissioner for Patents
Washington, D.C. 20231

Sir:

In the matter of the above-identified application for patent, notice is hereby given that the applicant claims as priority:

COUNTRY	APPLICATION NO	DAY/MONTH/YEAR
GREAT BRITAIN	9725318.1	28 NOVEMBER 1997

Certified copies of the corresponding Convention application(s) were submitted to the International Bureau in PCT Application No. **PCT/EP98/07740.**

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2. Patent application number *(The Patent Office will fill in this part)* — 28 NOV 1997 **9725318.1**

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

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   Patents ADP number *(if you know it)* — 04008074001

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4. Title of the invention — MAGNETIC ENERGY STORAGE

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I/We request the grant of a patent on the basis of this application.

Signature J.Y.&G.W.

Date 28-11-1997

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Technical Field

This invention relates to a superconducting magnetic energy storage device, generally denominated SMES.

Background of the Invention

The concept of superconducting magnetic energy storage (SMES) is well know. The principle of SMES is that energy is stored as magnetic energy in a coil having an inductance L. The amount of energy that theoretically can be stored in a superconductive coil is given by 1/2.L* I2, where I is the dc current.

The inductance L of a coil is given through the well-known relationship:

$$L = \frac{\mu_0 \mu_r N^2 A}{l}$$

where 0 = 4 10-7 As / Vm, r the permeability of material in the magnetic circuit of a solenoid (which is 1 for air, and around 10000 or higher for oriented laminated quality steel, provided the magnetic flux density B is sufficiently low), N is the number of windings, A the cross-sectional area and l the length of the coil.

Since the magnetic energy E to be stored in an SMES is E = 1/2 L I2, it is evident that both current and inductance should be maximised. The maximum current is given through the properties of a superconductor at given temperature, magnetic field and current density.

The inductance could be maximised by utilising a material in the magnetic circuit with a high permeabilty. Unfortunately, no materials are known that have a high permeability at high flux densities, in fact at B around 2 Tesla, even the best materials go into saturation, and in addition, core losses (hysteresis and eddy) increase drastically in the saturation region. If the magnetic moments of a material are perfectly aligned, it is theoretically possible to reach a maximum flux density of 2.12 Tesla for irion. Due to the high currents of superconductors, the flux densities are also high, in fact densities of 5 T and more are not uncommon. Thus magnetic material should not be included in the magnetic circuit, at least not in regoins of high B. In general, r is then equal to one.
The inductance can also be increased by choosing a high number of windings N. If a solenoid is wound, then the winding density, that is the number of windings per unit length, is determined by the cross-sectional area of the conductor and its insulation.

The ratio of cross-sectional area to length is also an important parameter for the inductance. The aim should be to achieve a large cross-section and a short coil length. Thus pancake- or disk windings are often designed as a preferred coil for reaching high inductances.

SMES have a high efficiency and high energy density compared with competing systems for storing energy. SMES can have a rapid response to demands of storing or discharging. And, SMES can be used not only for load-leveling but also for load-following, for spinning reverse, for transient stabilization and for synchronous resonance damping. SMES could provide not only energy savings but also a larger freedom of power system operation.

Normally the SMES are built for storing energy up to about 1 MW, but there is a demand for SMES with higher energy storage capability. Current solutions for larger SMES involve oversizing of equipment and the usage of multiple feeders connected to different transmission systems.

Conventional SMES devices operate with high current source at low voltage. When used in a ac power system an ac-dc converter can be used for converting the power to and from the SMES. Operation of SMES connected to power networks will include a transformer.

SMES are normally built as a coil. In order to maximize the storage capability, the inductance shall be as high as possible. Therefore, the superconductor is wound into a pancake, for example a 4 T background coil for SMES as described in " Design and construction of the 4 T background coil for the navy SMES cable test apparatus", IEEE Transaction on applied superconductivity, vol 7, no 2, June 1997. The SMES are normally connected to voltages up to around 500 V and currents around 1000 A.

A large SMES for 30MW is described in Transactions on Applied Superconductivity, vol 7, No 2, June 1997 " Quench Protection and Stagnant Normal Zones in a Large Cryostable SMES" and involve a coil assembled from a multiple double pancake structure. The application of that SMES requires a high power discharge and the operating voltage is desired to be up to 3.4 kV.

Another method of storing magnetic energy can be by winding the conductor directly as a solenoid. An example of a test coil is described in "Design, manufacturing and cold test of superconducting coil and its cryostat for SMES applications", IEEE Transactions on applied superonductivity, Vol 7, No 2, June 1997, where a solenoid consists of a NbTi conductor with 4500 turns, 30 layers and an inner winding radius of 120 mm.

Summary of Invention

The aim of the present invention is to have a high voltage system comprising an SMES, where the superconducting conductors of the SMES are insulated against high voltage and that the insulation is concentric around the conductors.

By this design the SMES can be made from cable-like conductors, which can be manufactured according to convention principles of cable manufacturing. The insulation shall be such that it can withstand high voltages in the range of 1 kV and upwards to the voltages used for high voltage dc current transmission.

The invention allows a high voltage system comprising an SMES system. The SMES can be coupled to a high voltage network. This means that load-following can be effected on a transmission-or distribution network and not only for a specific use on lower voltage as is the case with the SMES of today. This opens up possibilities to use SMES for storing energy to smooth load variations in a high voltage network on for example day-night basis or east-west basis. Also, an SMES on high voltage can be capable of injecting large amounts of energy into a system under a short time , that is injecting a large amount of real power, which will allow for good control of the system.

The present invention allows a high voltage system comprising an SMES system which can be directly coupled to a high voltage without the need to transform the voltage down. With high voltage is mean voltages up to 800 kV and even above that.

This can be achieved by insulating the conductor with an insulation system that can withstand high voltages. Such insulation systems are known for example from high voltage dc transmission systems.

An advantage with an SMES operating at high voltages is that charging and discharging can be rapid. It is normally very time-consuming to charge, at least the larger, SMES and by being able to connect the SMES to a high voltage the charging time can be substantially reduced. Also the power that can be delivered from the SMES is increased by increasing the voltage over the SMES.

Another advantage is that an SMES can be installed close to a large power generating unit, such as a nuclear power station. At a rapid close-down of a nuclear power station, there are large strains on the network. These could be effectively smoothed by a high voltage SMES, that could inject the corresponding power into the system and then allow for a slow ramp down of the power.

Another advantage of a high voltage SMES is that there is no need for a transformer for transforming power to and from the SMES. The SMES can be directly coupled to a transmission or distribution network without intermediate step-up transformers. The elimination of transformers in the system will lead to higher efficiency of the system. The performance of the SMES system will be greatly improved by being able to connect the SMES directly to a power network and by the increased efficiency that is created by the reduction of the number of components in the system.

Another advantage is that the SMES is wholly insulated in such a way that there is no electric field outside the superconducting cable. This will facilitate the design of the mechanical structure holding the cables. It will be possible to scale up the SMES with less problems with the mechanical stability of the SMES.

Another advantage of an SMES with high voltage insulation is that discharges that normally occur in the electric system will be prevented by the insulation system and the risk for bubble formation in the cooling medium is therefore reduced.

According to one aspect of the present invention an SMES device comprising a coil for connection in series with a dc voltage source and wound from a high-temperature

superconducting cable having superconducting means which, in use, is maintained at cryogenic temperatures below its critical temperature and which is surrounded by electrical insulation, and switch means for short-circuiting the coil, is characterised in that the said electrical insulation comprises an inner layer of semiconducting material electrically connected to said superconducting means, an outer layer of semiconducting material at a controlled electric potential, e.g. earth potential, along its length and an intermediate layer of solid polymeric electrically insulating material positioned between said inner and outer layers.

In this specification the term "semiconducting material" means a material which has a considerably lower conductivity than an electrical conductor but which does not have such a low conductivity that it is an electrical insulator. Typically, but not exclusively, a "semiconducting material" should have a resistivity of from 1 to 1000 Ohm-cm, preferably from 10 to 500 Ohm-cm and most preferably 50 to 100 Ohm-cm.

By connecting the coil directly to a high voltage dc voltage source, e.g. to a high voltage ac-dc converter, charging and discharging of the coil is simplified. In particular, in an ac power transmission system, the need to transform the ac voltage down prior to connection to an ac-dc converter is eliminated. By holding the semiconducting outer layer at a controlled electric potential, e.g. ground or earth potential, at intervals along its length, the electric field generated by the superconducting means, is contained within the electrical insulation.

Conveniently the coil and switch means are enclosed within a cryostat for maintaining the temperature of the superconducting means below its critical temperature (Tc). Alternatively, or in addition, the superconducting means may be internally cooled by a cryogenic fluid, e.g. liquid nitrogen, and externally thermally insulated. For example thermal insulation may conveniently be provided between the superconducting means and the surrounding electrical insulation. In some cases the electrical insulation can also function as thermal insulation.

By using for the intermediate layer only materials which can be manufactured with few, if any, defects and by providing the intermediate layer with the spaced apart inner and outer layers of semiconducting material having similar thermal properties, thermal and electric loads within the insulation are reduced. In particular the insulating intermediate layer and the semiconducting inner and outer layers should have at least substantially the same coefficients of thermal expansion (a) so that defects caused by different thermal expansions when the layers are subjected to heating or cooling will not arise. Ideally the electrical insulation is of substantially unitary construction. The layers of the insulation may be in close mechanical contact but are preferably joined or united together. Preferably, for example, the radially adjacent layers will be extruded together around the superconducting means. The superconducting cable is flexible at normal ambient temperatures and thus can be bent or flexed into its desired winding shape prior to operation at cryogenic temperatures.

Conveniently the electrically insulating intermediate layer comprises solid thermoplastics material, such as low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethylpentene

(PMP), cross-linked materials, such as cross-linked polyethylene (XLPE), or rubber insulation, such as ethylene propylene rubber (EPR) or silicone rubber. The semiconducting inner and outer layers may comprise similar material to the intermediate layer but with conducting particles, such as particles of carbon black or soot, embedded therein. Generally it has been found that a particular insulating material, such as EPR, has similar mechanical properties when containing no, or some, carbon particles.

The screens of semiconducting inner and outer layers form substantially equipotential surfaces on the inside and outside of the insulating intermediate layer so that the electric field, in the case of concentric semiconducting and insulating layers, is substantially radial and confined within the intermediate layer. In particular, the semiconducting inner layer is arranged to be in electrical contact with, and to be at the same potential as, the superconducting means which it surrounds. The semiconducting outer layer is designed to act as a screen to prevent losses caused by induced voltages. Induced voltages could be reduced by increasing the resistance of the outer layer. Since the thickness of the semiconducting layer cannot be reduced below a certain minimum thickness, the resistance can only be reduced by selecting a material for the layer having a higherresistivity. However, if the resistivity of the semiconducting outer layer is too great the voltage potential between adjacent spaced apart points at a controlled, e.g. earth, potential will become sufficiently high as to risk the occurrence of corona discharge with consequent erosion of the insulating and semiconducting layers. The semiconducting outer layer is therefore a compromise between a conductor having low resistance and high induced voltage losses but which is easily connected to a controlled electric potential, typically earth or ground potential, and an insulator which has high resistance with low induced voltage losses but which needs to be connected to the controlled electric potential along its length. Thus the resistivity ρ_s of the semiconducting outer layer should be within the range $\rho min<\rho_s<rmax$, where ρmin is determined by permissible power loss caused by eddy current losses and resistive losses caused by voltages induced by magnetic flux and ρmax is determined by the requirement for no corona or glow discharge.

If the semiconducting outer layer is earthed, or connected to some other controlled electric potential, at spaced apart intervals along its length, there is no need for an outer metal shield and protective sheath to surround the semiconducting outer layer. The diameter of the cable is thus reduced allowing more turns to be provided for a given size of winding.

The insulation system can be extruded on the conductor or a lapped concept can be used. This can include both the semi-conducting layers and the electrically insulating part. An insulation can be made of an all-synthetic film with inner and outer semi - conducting layers made of a polymeric thin film of for example PP; PET , LDPE or HDPE with conducting particles such as carbon black or metallic particles embedded.

For the lapped concept a sufficiently thin film will have buttgaps smaller than the so called Paschen minima, thus rendering liquid impregnation unnecessary. A dry,

wound multilayer thin film insulation has also good thermal properties and could be combined with a superconducting pipe as electric conductor and have the coolant, such as liquid nitrogen pumped through the pipe .

Another example of insulation system is similar to a conventional cellulose based cable, where a thin cellulose based or synthetic paper or non-woven material is lapped around a conductor. In this case the semi-conducting layers can be made of cellulose paper or non-woven material made from fibres of insulating material and with conducting particles embedded. The insulating part can be made from the same base material or another material can be used.

Another example is obtained by combining the film and the fibrous insulating material, either as a laminate or as co-lapped. An example of this insulation system is the commercially available so called paper polypropylene laminate, PPLP, but several other combinations of film and fibrous parts are possible. In these systems various impregnations such as mineral oil or liquid nitrogen can be used.

The low temperture conductor may comprise low temperature superconductors, but most preferably comprises high-temperature superconducting (HTS) materials, for example HTS wires or tape helically wound on an inner tube. The HTS tape conveniently comprises silver-sheathed BSCCO-2212 or BSCCO-2223 (where the numerals indicate the number of atoms of each element in the [Bi, Pb]2 Sr2 Ca2 Cu3 Ox molecule) and hereinafter such HTS tapes will be referred to as "BSCCO tape(s)". BSCCO tapes are made by encasing fine filaments of the oxide superconductor in a silver or silver oxide matrix by a powder-in-tube (PIT) draw, roll, sinter and roll process. Alternatively the tapes may be formed by a surface coating process. In either case the oxide is melted and resolidified as a final process step. Other HTS tapes, such as TiBaCaCuO (TBCCO-1223) and YBaCuO (YBCO-123) have been made by various surface coating or surface deposition techniques. Ideally an HTS wire should have a current density beyond $j_c \sim 10^5$ Acm^{-2} at operation temperatures from 65 K, but preferably above 77 K. The filling factor of HTS in the matrix needs to be high so that the engineering current density $j_e \geq 10^4$ Acm^{-2}. j_c should not drastically decrease with applied field within the Tesla range. The helically wound HTS tape is cooled to below the critical temperature Tc of the HTS by a cooling fluid, preferably liquid nitrogen, passing through the inner support tube.

A cryostat layer may be arranged around the helically wound HTS tape to thermally insulate the cooled HTS tape from the electrically insulating material. Alternatively, however, the cryostat may be dispensed with. In this latter case, the electrically insulating material may be applied directly over the superconducting means. Alternatively a space may be provided between the superconducting means and the surrounding insulating material, the space either being a void space or a space filled with compressible material, such as a highly compressible foamed material. The space reduces expansion/contraction forces on the insulation system during heating from/cooling to cryogenic temperatures. If the space is filled with compressible material, the latter can be made semiconducting to ensure electrical contact between the semiconducting inner layer and the superconducting means.

Other designs of superconducting means are possible, the invention being directed to transformer windings, formed from superconducting cables of any

suitable design having a surrounding electrical insulation of the type described above. For example other types of superconducting means may comprise, in addition to internally cooled HTS, externally cooled HTS or externally and internally cooled HTS. In the latter type of HTS cable, two concentric HTS conductors separated by cryogenic insulation and cooled by liquid nitrogen are used to transmit electricity. The outer conductor acts as the return path and both HTS conductors may be formed of one or many layers of HTS tape for carrying the required current. The inner conductor may comprise HTS tape wound on a tubular support through which liquid nitrogen is passed. The outer conductor is cooled externally by liquid nitrogen and the whole assembly may be surrounded by a thermally insulating cryostat.

According to another aspect of the present invention there is provided an electric power transmission system characterised in that an SMES device according to said one aspect is connected to a high dc voltage source.
The SMES device may also be connected to a high voltage dc source and be in the form of a cable and preferable a cable with high inductance. The cable can be made of conductor tape or wire with several layer and where all layers are wound in the same direction instead of as conventionally done, wind the layers in opposite direction in order to compensate for the inductance. Such cable and with an extruded insulation system could be directly incorporated into a transmission line, for example as one line of a bipolar dc system.
It is also possible to use such cable to build up a solenoid with high inductance .

The invention as herein described can also be used with conventional low-temperature superconductive materials and with coolants such as liquid helium.

It is also possible to use the invention with an ac source. The losses are larger for an ac SMES but if the losses are acceptable for the system to be designed, the principle of the invention is applicable. Brief Description of the Drawings

An embodiment of the invention will now be described, by way of example only, with particular reference to the accompanying drawings, in which:

Figure 1 is a circuit diagram of an SMES device according to the present invention;

Figure 2 is a schematic sectional view, on an enlarged scale, through part of one embodiment of a high-temperature superconducting cable from which the coil of the SMES device of Figure 1 is wound; and

Figure 3 is a schematic sectional view, on an enlarged scale, of another embodiment of high-temperature superconducting cable from which the coil of the SMES device of Figure 1 can be wound.

Figure 4 is a schematic view of two high voltage ac networks coupled together via a high voltage dc network and incorporating an SMES on the dc side.

Figure 5 is a schematic view of an SMES incorporated into a high voltage dc network.

Figure 6 is a schematic view of two converter stations with voltage source converters and combined with a high voltage bipolar dc link.

Figure 1 shows a coil 1 having an inductance L formed of high-temperature (Tc) superconducting (HTS) cable 12 (see Figure 2) which is connected with a high dc voltage source 2, e.g. the dc side of a high voltage ac-dc converter connected to an ac power transmission line. A switch 3 is connected in parallel with the high dc voltage source 2 and is operable to short-circuit the coil 1.

When the coil 1 is connected to the dc voltage source 2, a dc current I flows and charges the coil. Due to the high current density of the superconducting cable and its virtually zero resistance, energy is simply stored by closing the switch 3 and short-circuiting the coil. The energy in the coil is stored as magnetic energy having a value of $1/2LI^2$. The coil 1 is thus able to store electrical energy and to provide electrical power at a fast rate when required at times of peak consumption.

The superconducting cable 12 from which the coil 1 is formed comprises an inner tubular support 13, e.g. of copper or a highly resistive metal, such as copper-nickel, alloy, on which is helically wound elongate HTS material, for example BSCCO tape or the like, to form a superconducting layer 14 around the tubular support 13. A cryostat 15, arranged outside the superconducting layer, comprises two spaced apart flexible corrugated metal tubes 16 and 17. The space between the tubes 16 and 17 is maintained under vacuum and contains thermal superinsulation 18. Liquid nitrogen, or other cooling fluid, is passed along the tubular support 13 to cool the surrounding superconducting layer 14 to below its critical superconducting temperature Tc. The tubular support 13, superconducting layer 14 and cryostat 15 together constitute superconducting means of the cable 12.

Solid electrical insulation of plastics material is arranged outside the superconducting means. The electrical insulation comprises an inner semiconducting layer 20, an outer semiconducting layer 21 and, sandwiched between these semiconducting layers, an insulating layer 22. The layers 20-22 preferably comprise thermoplastics materials providing a substantially unitary construction. The layers may be in close mechanical contact with each other but are preferably solidly connected to each other at their interfaces. Conveniently these thermoplastics materials have similar coefficients of thermal expansion and are preferably extruded together around the inner superconducting means.

By way of example only, the solid insulating layer 22 may comprise cross-linked polyethylene (XLPE). The inner and outer semiconducting layers may comprise, for example, a base polymer, such as ethylene-propylene copolymer rubber (EPR) or ethylene-propylene-diene monomer rubber (EPDM), and highly electrically conductive particles, e.g. particles of carbon black embedded in the base polymer. The resistivity of these semiconductive layers may be adjusted as required by varying the type and proportion of carbon black added to the base polymer. The following gives an example of the way in which resistivity can be varied using different types and quantities of carbon black.

Base Polymer	Carbon Black Type	Carbon Black Quantity (%)	Volume Resistivity Ω-cm
Ethylene vinyl acetate copolymer/ nitrite rubber	EC carbon black	~15	350-400
-"-	P-carbon black	~37	70-10
-"-	Extra conducting carbon black, type I	~35	40-50
-"-	Extra conducting black, type II	~33	30-60
Butyl grafted polyethylene	-"-	~25	7-10
Ethylene butyl acrylate copolymer	Acetylene carbon black	~35	40-50
-"-	P carbon black	~38	5-10
Ethylene propene rubber	Extra conducting carbon black	~35	200-400

The outer semiconductive layer 21 is connected to a desired controlled electric potential, e.g. earth potential, at spaced apart regions along its length, the specific spacing apart of adjacent controlled potential or earthing points being dependent on the resistivity of the layer 21.

The semiconducting layer 21 acts as a static shield and by controlling the electric potential of the outer layer, e.g. to earth potential, it is ensured that the electric field of the superconducting cable is retained within the solid insulation between the semiconducting layers 20 and 21. Losses caused by induced voltages in the layer 21 are reduced by increasing the resistance of the layer 21. However, since the layer 21 must be at least of a certain minimum thickness, e.g. no less than 0.8 mm, the resistance can only be increased by selecting the material of the layer to have a relatively high resistivity. The resistivity cannot be increased too much, however, else the voltage of the layer 21 mid-way between two adjacent earthing points will be too high with the associated risk of corona discharges occurring.

Instead of, or in addition to, internally cryogenically cooling the HTS cable 12, the coil 1 and switch 3 may be enclosed within a cryostat 6 (shown schematically in dashed lines in Figure 1) for keeping the coil 1 at temperatures below the critical temperature of the superconducting means. In this case the thermally insulating cryostat 15 need not be included in the HTS cable described above with reference to Figure 2. Figure 3 shows a typical design of cable having no cryostat 15. In this case the electrical insulation, provided by the layers 20-22, is extruded directly over the superconducting layer 14 wound on the tubular support 13. Although not shown, an annular gap may be provided between the electric insulation and the layer 14 to cater for the differences in thermal expansion/contraction of the electrical insulation and the layer 14. This annular gap could be a void space or could be filled

with compressible material, such as highly compressible foam material. If such an annular gap is provided, the semiconducting inner layer 20 is preferably placed in electrical contact with the superconducting layer 14. For example if the compressible material is included in the annular gap the foam material may be made semiconducting.

Figure 4 shows two high voltage ac networks, N1 and N2. TIY and T2Y are convertertransformers in Y/Y coupling , T1D and T2D are convetertransformers in Y/D coupling.

SCR11- SCR22 are seriesconnected 6-puls linecommutated bridge-connected converters.

The converters SCR11, SCR12 are linked with the converters SCR21, SCR22 via an dc link DCL, which cd link comprises en energy storage in the form of an SMES.

The voltage over the converters SCR11, SCR12 is called U1 and over SCR21,SCR22 U2. U1 and U2 are each in a conventional manner controlled by control equipment connected with its respective converter (not shown in figure). The current id runs through the dc link and the SMES.

$U1 - U2 = L * dI/dt$, which means that charging and discharging of the SMES can be controlled by the controlangles of the convertors. One or both converters can charge or discharge the SMES. By controlling U1=U2 , the content of energy of the SMES can be unaffected.

Figure 5 shows the same basic structure as figure 4 . In case the SMES is used as a storage for the ac network N1 , it is charged via the converters SCR11, SCR12 with the switch S1 closed and the switch S2 open. When the SMES is charged,could for example the current through the coil be measured and charging continue until a nominal value is reached . When the SMES is fully charged S1 opens and S2 closes. For feeding the network N1, for example in the case of a power loss on the network, S1 closes and S2 is opened.

For the case the SMES is part of an high voltage dc transmission system with a dc link, a polecontrol device, PCM, is needed when providing the network N2 with power.

Figure 6 shows two voltage -controlled converters VSC1 and VSC2, which are connected via a dc link in the form of a double cable TC. The dc link is bipolar in that the capacitors C11, C12 respectively C21, C22 are connected to ground in its connecting piont. An SMES is arranged at one pole of the converter VSC1.
It is also possible to arrange the SMES in the form of a cable as one part of the bipolar dc link.

CLAIMS

1. An SMES device comprising a coil (1) for connection in series with a dc voltage source (2) and wound from a high-temperature superconducting cable (12) having high-temperature superconducting means (14) which, in use, is maintained at cryogenic temperatures below its critical temperature (Tc) and which is surrounded by electrical insulation (20-22), and switch means (3) for short-circuiting the coil (1), characterised in that the said electrical insulation comprises an inner layer (20) of semiconducting material electrically connected to said superconducting means, an outer layer (21) of semiconducting material at a controlled electric potential along its length and an intermediate layer (22) of solid polymeric electrically insulating material positioned between said inner and outer layers (20 and 21).

2. An SMES device according to claim 1, characterised in that the device further comprises a cryostat (6) in which the coil (1) and switch means (3) are enclosed.

3. An SMES device according to claim 1 or 2, characterised in that said high-temperature superconducting (HTS) means comprises at least one layer (14) of high- temperature superconducting (HTS) material, cooling means (13) for cryogenically cooling the layer(s) (14) of HTS material below the critical temperature (Tc) of the HTS material, and thermally insulating means (15) surrounding the layer(s) (14) of HTS material and the cooling means (13).

4. An SMES device according to claim 3, characterised in that the cooling means (14) comprises a support tube (13) through which cryogenic cooling fluid is passed and in that the at least one layer (14) of HTS material comprises high-temperature superconducting (HTS) tape or conductors wound in a helical layer on said support tube (13).

5. An SMES device according to claim 4, characterised in that the thermally insulating means (15) comprises an annular space under vacuum and containing thermal insulation (18).

6. An SMES device according to any one of the preceding claims, characterised in that the semiconducting outer layer (21) has a resistivity of from 1 to 1000 ohm-cm.

7. An SMES device according to claim 6, characterised in that the said outer layer (21) has a resistivity of from 10 to 500 ohm-cm, preferably from 50 to 100 ohm-cm.

8. An SMES device according to any one of claims 1 to 7, characterised in that the resistance per axial unit length of the semiconducting outer layer (21) is from 5 to 50,000 ohm.m^{-1}.

9. An SMES device according to any one of claims 1 to 7, characterised in that the resistance per axial unit of length of the semiconducting outer layer (21) is from 500 to 25,000 ohm.m-1, preferably from 2,500 to 5,000 ohm.m^{-1}.

10.An SMES device according to any one of the preceding claims, characterised in that the semiconducting outer layer (21) is contacted by conductor means at said controlled electric potential at spaced apart regions along its length, adjacent contact regions being sufficiently close together that the voltages of mid-points between adjacent contact regions are insufficient for corona discharges to occur within the electrically insulating means.

11.An SMES device according to any one of the preceding claims, characterised in that said controlled electric potential is at or close to earth potential.

12.An SMES device according to any one of the preceding claims, characterised in that the said intermediate layer (22) is in close mechanical contact with each of said inner and outer layers (20 and 21).

13.An SMES device according to any one of claims 1 to 11, characterised in that the said intermediate layer (22) is joined to each of said inner and outer layers (20 and 21).

14.An SMES device according to any one of the preceding claims, characterised in that the strength of the adhesion between the said intermediate layer (22) and each of the semiconducting inner and outer layers (20, 21) is of the same order of magnitude as the intrinsic strength of the material of the intermediate layer.

15.An SMES device according to claim 13 or 14, characterised in that the said layers (20-22) are joined together by extrusion.

16.An SMES device according to claim 15, characterised in that the inner and outer layers (20, 21) of semiconducting material and the insulating intermediate layer (22) are applied together over the superconducting means through a multi layer extrusion die.

17.An SMES device according to any one of the preceding claims, characterised in that said inner layer (20) comprises a first plastics material having first electrically conductive particles dispersed therein, said outer layer (21) comprises a second plastics material having second electrically conductive particles dispersed therein and said intermediate layer (22) comprises a third plastics material.

18.An SMES device according to claim 17, characterised in that each of said first, second and third plastics materials comprises an ethylene butyl acrylate copolymer rubber, an ethylene-propylene-diene monomer rubber (EPDM) or an ethylene-propylene copolymer rubber (EPR), LDPE, HDPE, PP, PB, PMP, XLPE, EPR or silicone rubber.

19.An SMES device according to claim 17 or 18, characterised in that said first, second and third plastics materials have at least substantially the same coefficients of thermal expansion.

20. An SMES device according to claim 17, 18 or 19, characterised in that said first, second and third plastics materials are the same material.

21. An electric power transmission system comprising an SMES device according to any one of the preceding claims connected to a high dc voltage source.

22. A high voltage system comprising an SMES, characterised in that the SMES have superconductive conductors that are insulated against high voltage and that the insulation is concentric around the conductor.

23. A high voltage system according to claim 22, characterised in that the system comprises a high voltage network and that the SMES can be directly connected to the high voltage network without an intermediate transformer.

24. A high voltage system according to claim 23, characterised in that the network is a high voltage dc network.

25. A high voltage system according to claim 24, characterised in that the dc network is at a voltage exceeding 10 kV.

26. A high voltage system according to claim 23, characterised in that the SMES is coupled to a high voltage ac network via a converter.

27. A high voltage system according to claim 24 comprising several ac networks connected via the dc network and the SMES directly coupled to the high voltage dc network without intermediate transformer and that the dc network is so connected to the ac networks that the SMES can provide the ac networks with power.

28. A high voltage system according to any of the preceding claims, characterised in that the SMES comprises a coil.

29. A high voltage system according to any of the preceding claims, characterised in that the SMES comprises a cable without turns.

30. A high voltage system according to claims 27 and 29, characterised in that the SMES is one part of a bipolar dc link.

31. A high voltage system according to any of the preceding claims, characterised in that said superconductive conductor is insulated by an extruded solid insulation formed around the conductor and that said insulation have a first integral part forming an inner layer in electric contact with the conductor and having semi conducting properties and a second integral part forming an outer layer around the insulation and having semiconducting properties.

32. A high voltage system according to any of claims 22 to 30, characterised in that said superconductive conductor is insulated by an insulation system comprising an all-synthetic film, lapped around the conductor and with an inner part in electric contact with the conductor and having semiconducting properties and an outer part

surrounding the insulating part and having semiconducting properties.

33.A high voltage system according to any of claims 22 to 30, characterised in that said superconductive conductor is insulated by an insulation system comprising one or more of a cellulose-based , synthetic paper or non-woven fibre material , colapped or laminated with an synthetic film and an inner part in electric contact with the conductor and having semiconducting properties and an outer part around an insulating part and having semiconducting properties.

34.A high voltage system according to claim 31, 32 or 33, characterised in that a cooling medium for cooling said superconductive conductor is arranged to flow within the conductor.

35.A high voltage system according to claim 31, 32 or 33, characterised in that a cooling medium for cooling said superconductive conductors is arranged outside of the conductor.

FIG 1

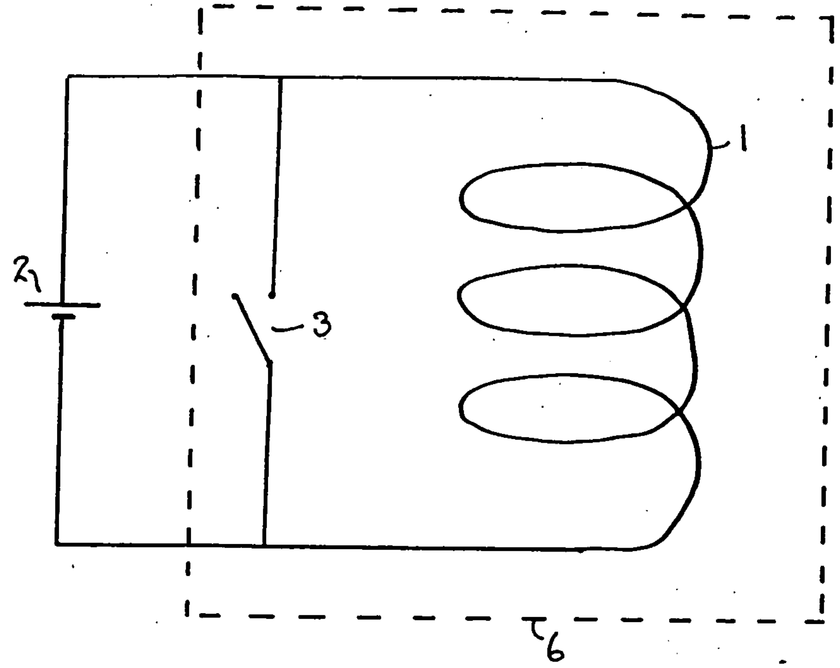
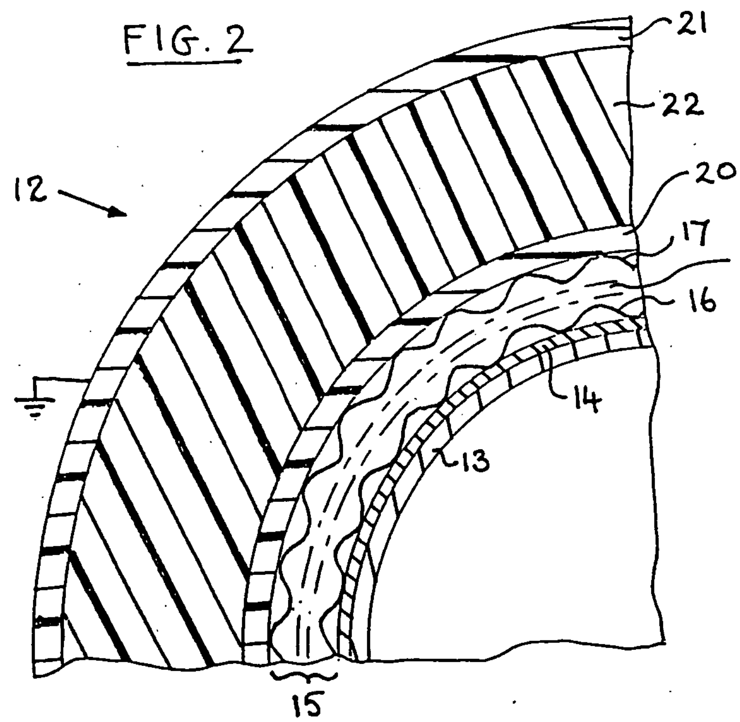


FIG. 2



M 30·11·98

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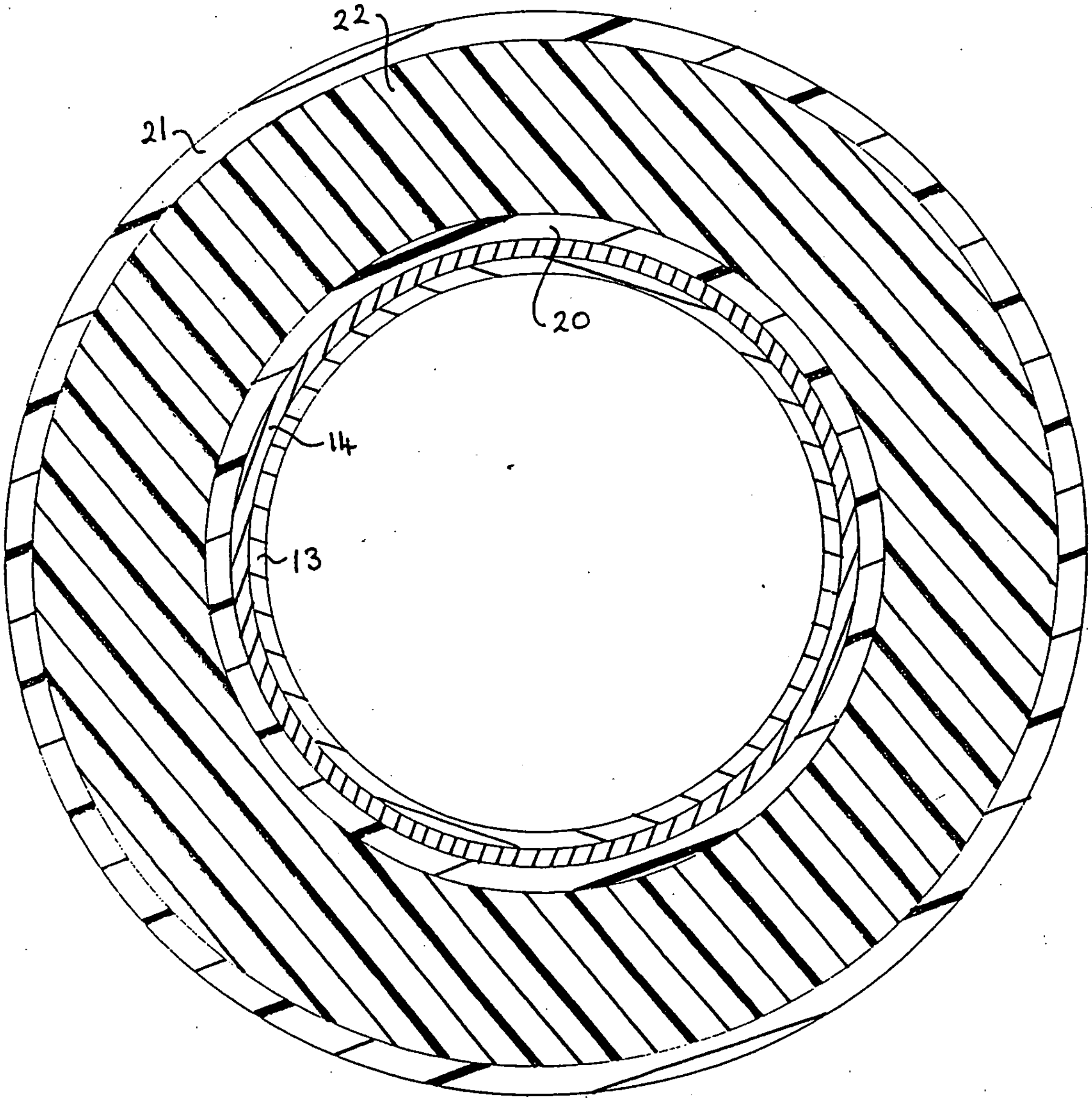
FIG. 3



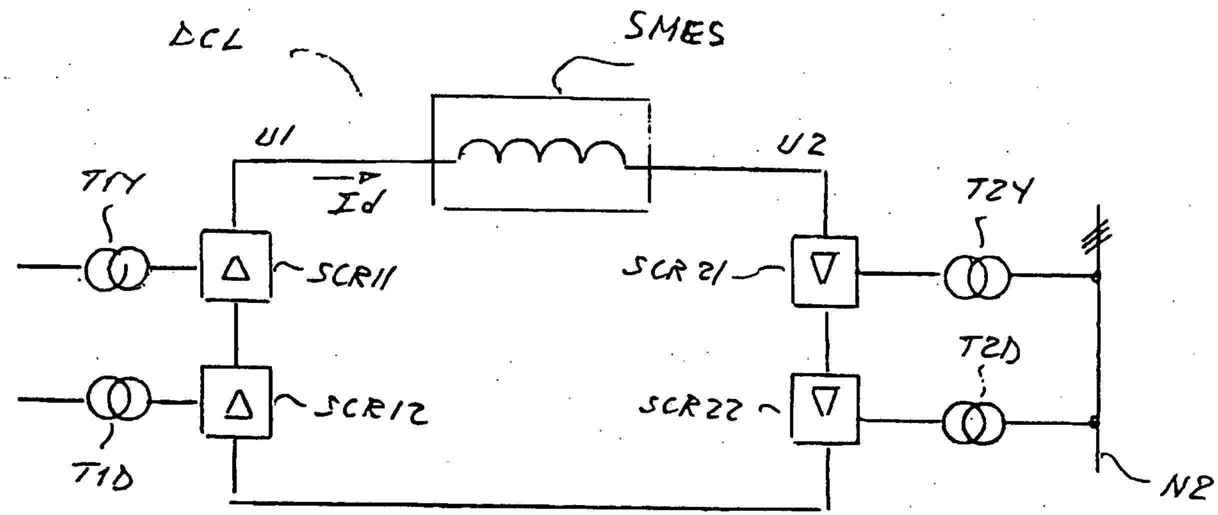


Fig. 4

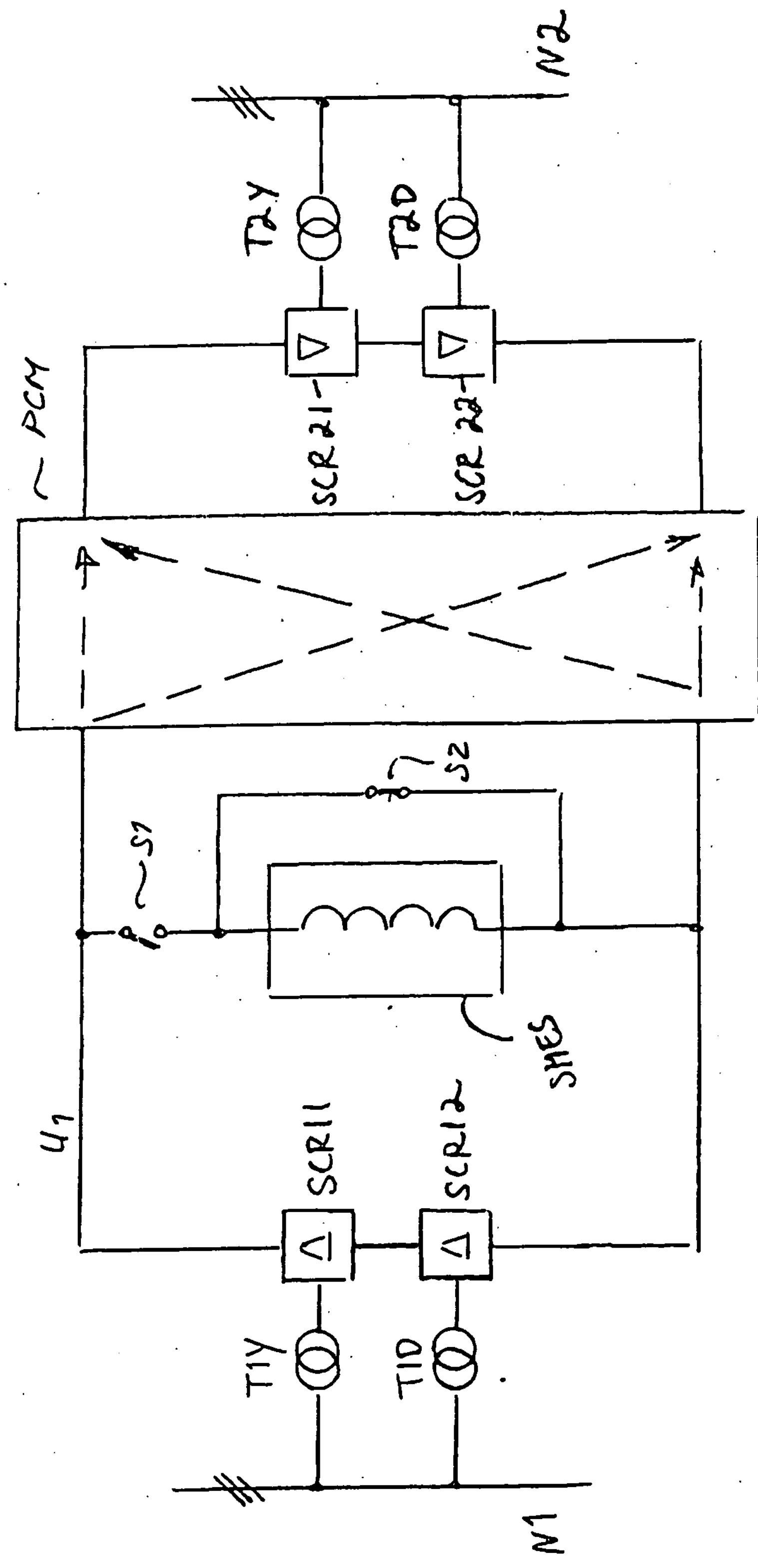


Fig. 5

M 20·11·98

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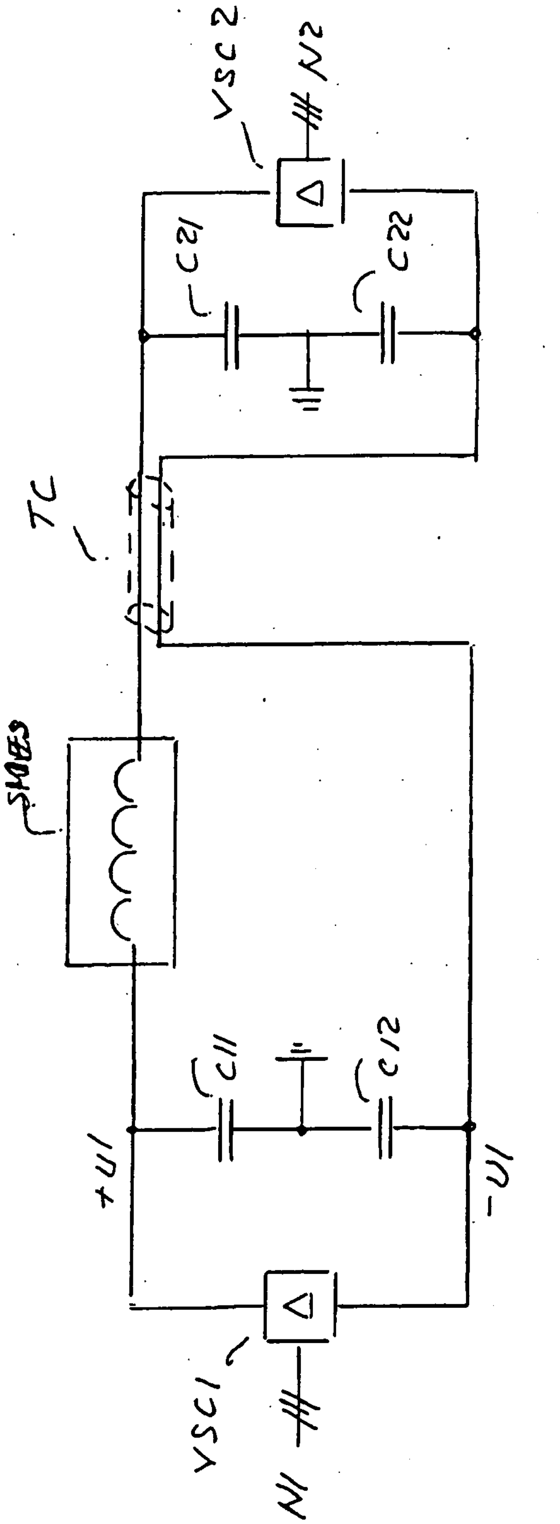

Fig. 6